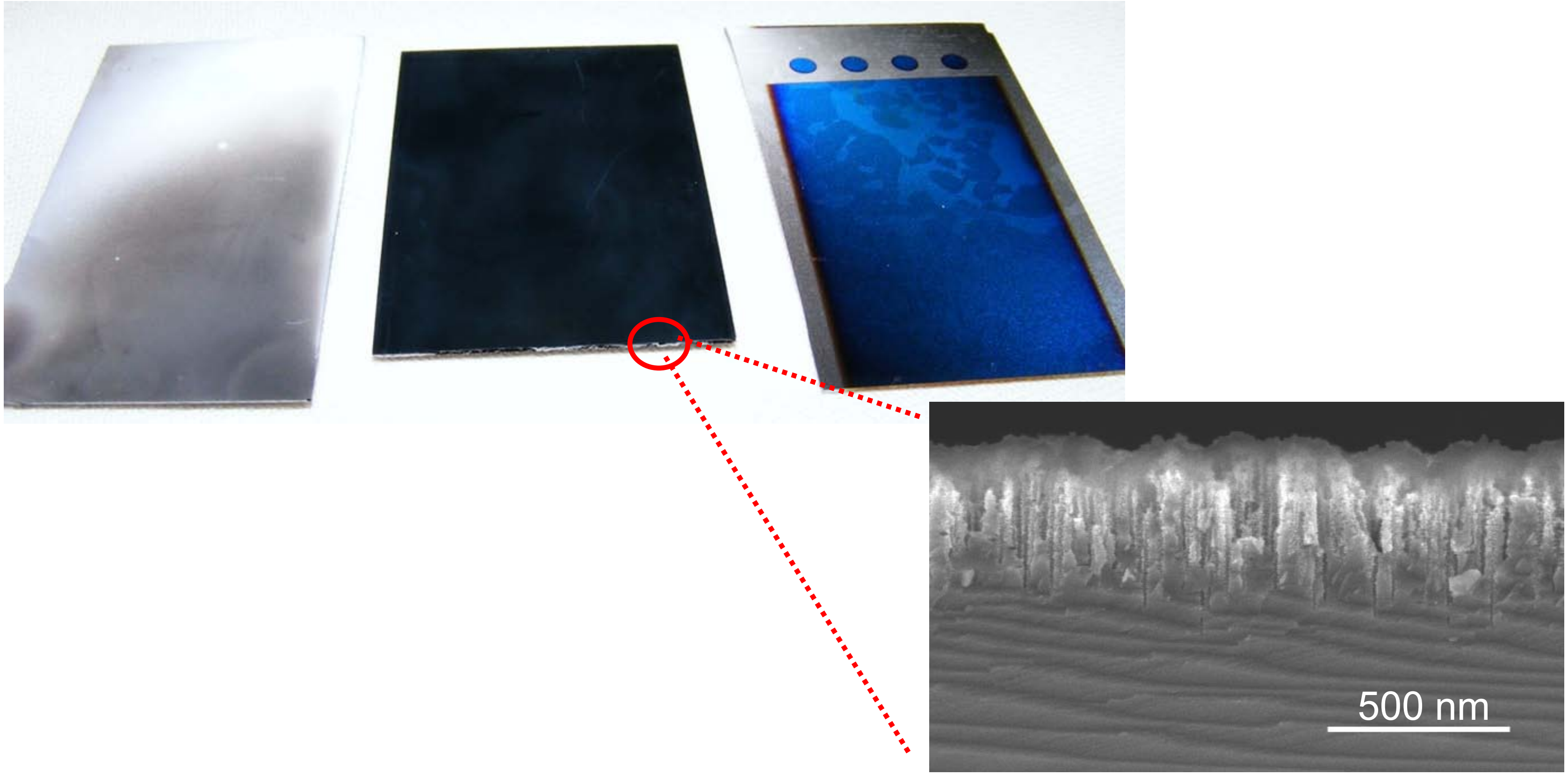

Black Silicon Anti-Reflection: Increased Wafer Silicon Efficiency with Reduced Manufacturing Costs

Program Team: PV

Howard M. Branz
National Renewable Energy Laboratory
Phone: 303-384-6694
Email: howard.branz@nrel.gov
May 26, 2010

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Timeline

- Project start date: Feb. 01, 2010
- Project end date: Jan. 31, 2012
- Percent complete: 12%

Budget

- Total project funding
  - DOE: $1M
- Funding received in FY10: $333k
- Funding for FY11: $500k

Barriers

- Poor broad-spectrum and off-angle anti-reflection (AR) performance in Si PV
- Costly vacuum-based interference AR coatings
- Toxic and greenhouse gases

Partners

- Project lead: NREL
- Interactions/collaborations: 6 crystalline-Si PV companies,2 chemical companies

  2 start-up companies

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Challenges, Barriers or Problems

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- Conventional interference-based AR on crystalline-Si
  - Reflection losses 3-10% across spectrum
  - Poor angular acceptance of incident photons
  - Costly vacuum-based deposition (normally SiN_x)
    - Mostly PECVD
      - hazardous process gases
      - greenhouse-gas cleaning gases
    - Some sputtering

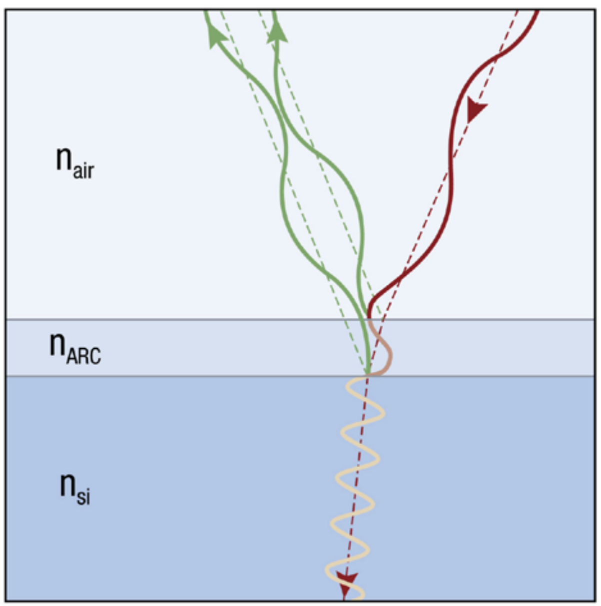
- NREL one-step, liquid black Si etch
  - Excellent AR over broad spectrum
    - potential to improve solar energy conversion efficiency
  - Improved angular acceptance for high annual energy production
  - Inexpensive liquid bath texture etch

Conventional Anti-Reflection Combines Coating and Texture

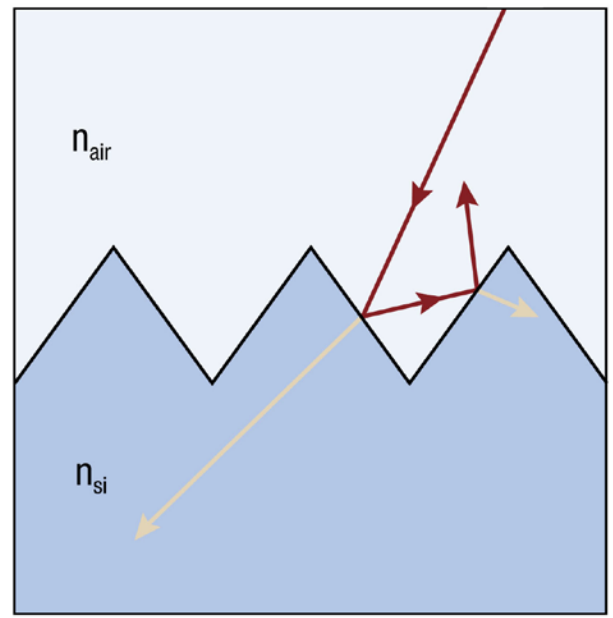
Multicrystal Si: ~7% reflection loss

Single crystal Si: ~ 3% reflection loss

Antireflection coating



Textured surface



- Interference anti-reflection coating
- Suppress reflection at one fixed wavelength
- Requires vacuum-based deposition tools

- Multiple reflections broaden spectrum
- μm-scale surface texture
- Broad-band AR only at *near normal* angles

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Background: NREL's One-Step, All-Liquid Black Si Etch

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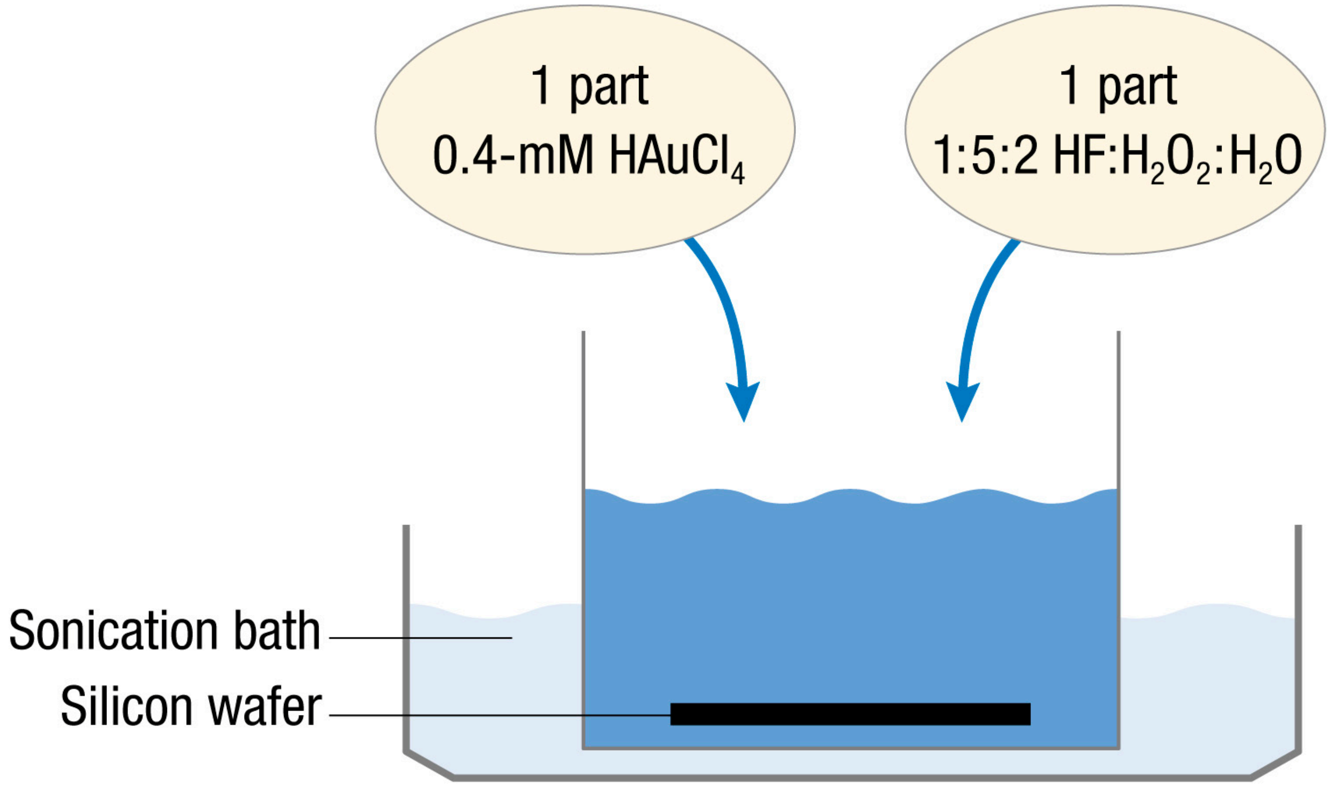

- Excellent AR after 3-min etch at room temperature, <1 min at 40°C

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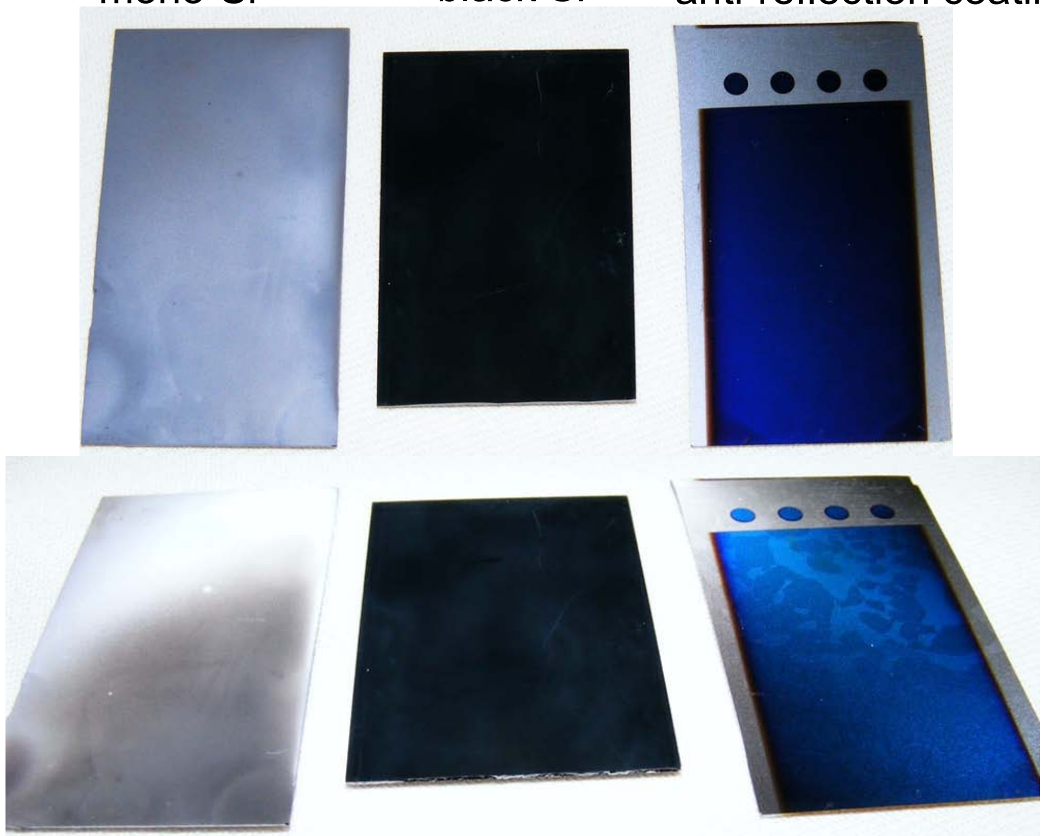
Background: Appearance of Black Si

μm-scale textured mono-Si | 3-min black Si | μm-scale textured + anti-reflection coating

Near normal angle:

Tilted angle:



- Conventional AR scheme has low reflection at near normal angle but high reflection at titled angle
- Black Si surface remains dark at various angles

Background: Black Si Reflectance below 2% for entire spectrum

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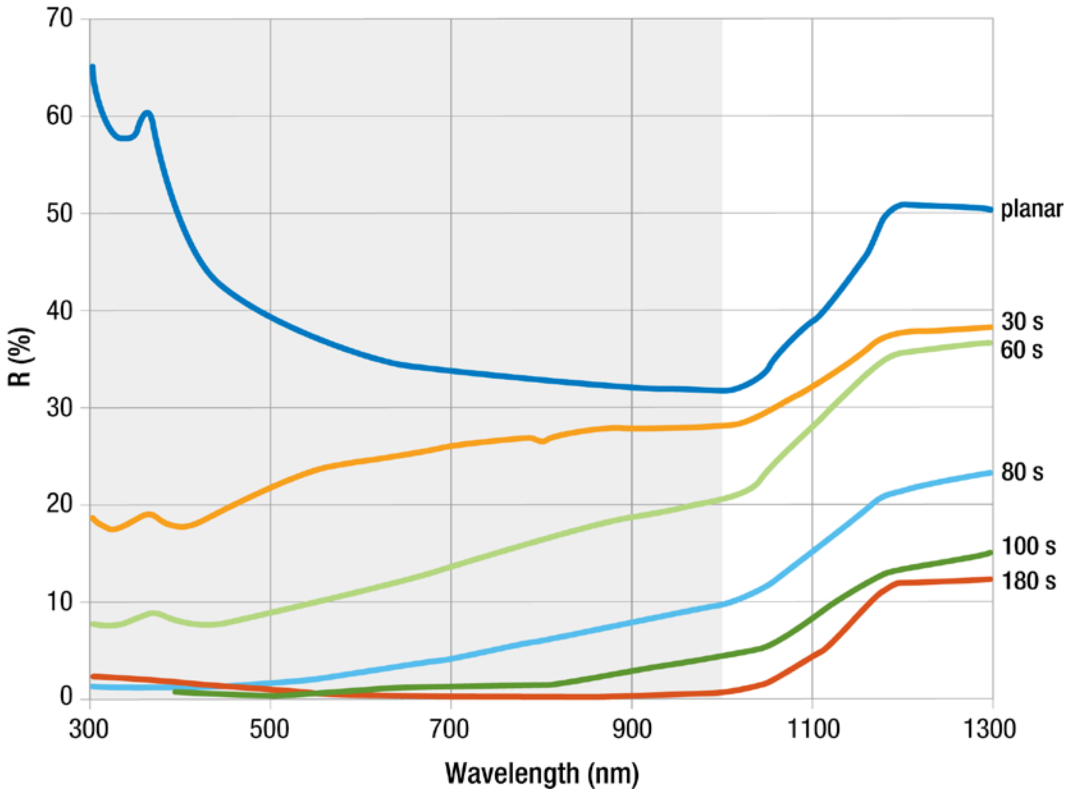
Branz et al. APL, 2009



- Reflection suppression starts at short wavelength and progresses to long wavelength as black Si etch time increases

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Background: SEM Image of 3-Min Black Si

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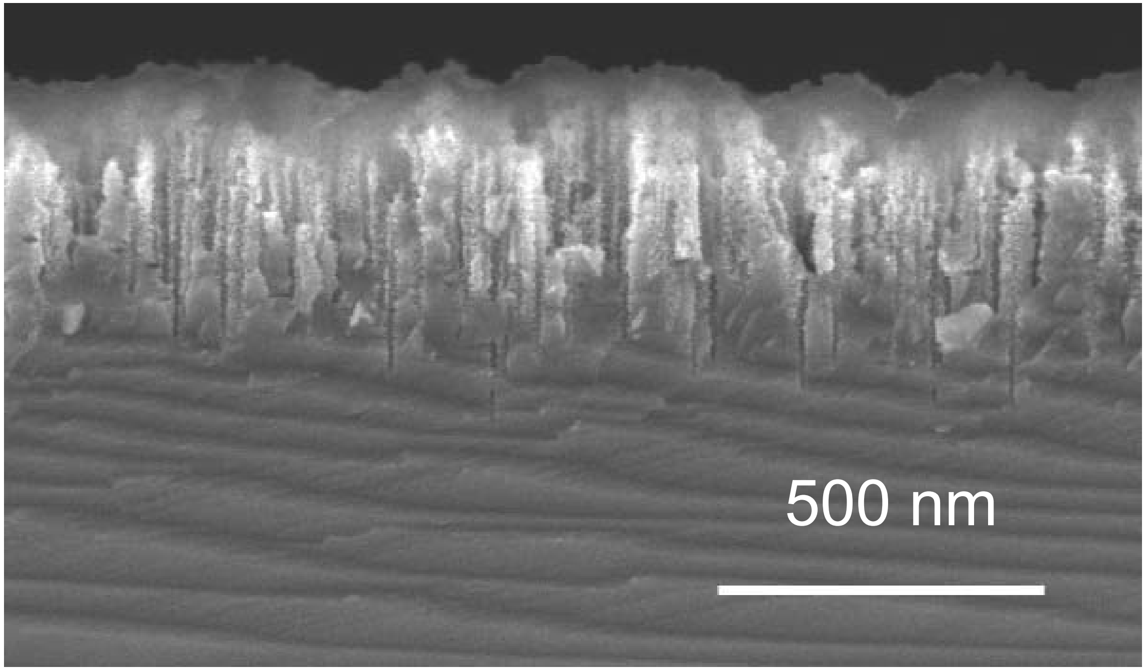
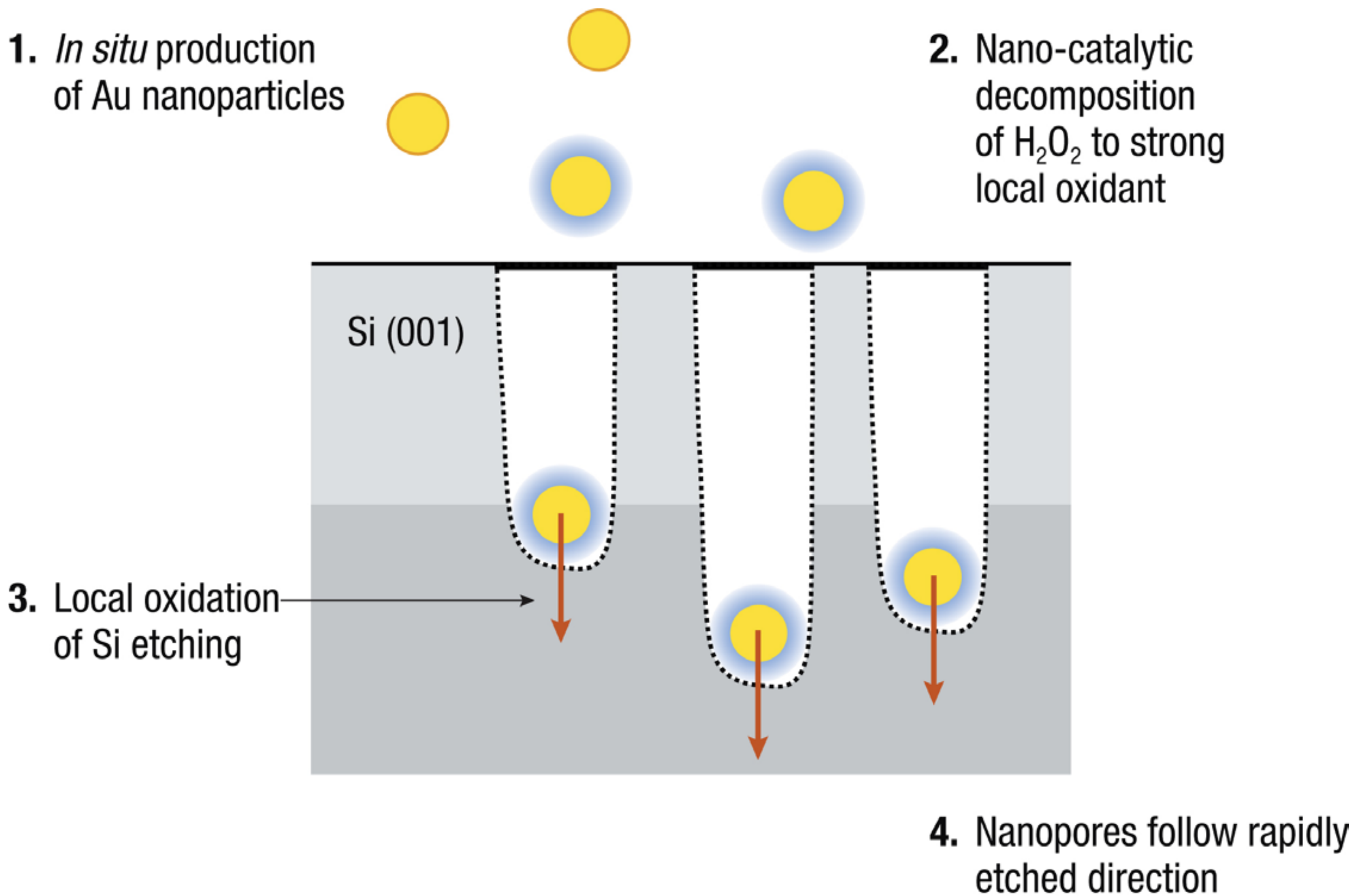
Branz et al. APL, 2009



- Nano-porous surface layer
- 3-min black Si etch at room temperature produces pores in diameter of ~10 nm and depth of ~600 nm

Mechanism: Nano-Pore Formation

Branz et al. APL, 2009



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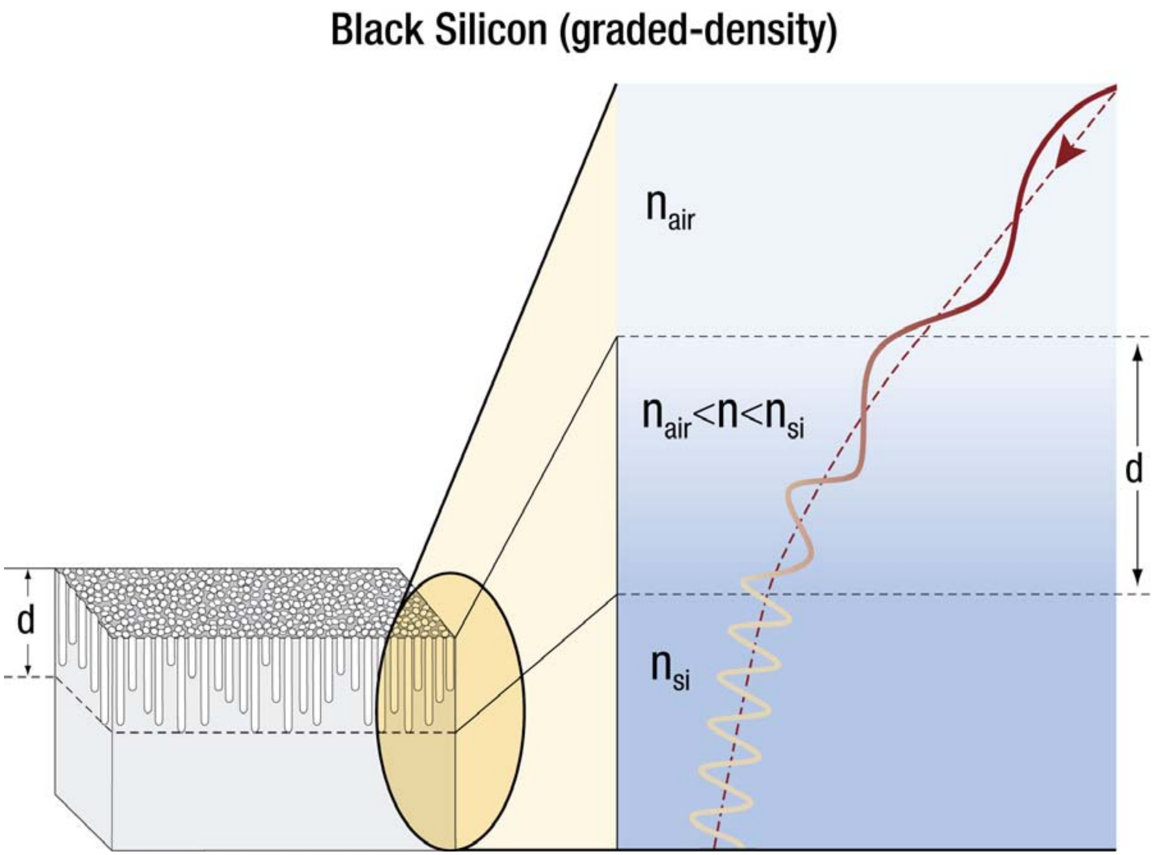
Background: Optics

Branz et al. APL, 2009



- Nano-porous graded-density surface
- No abrupt interface between ambient and Si means no reflection
- Good AR at all angles since it does not rely on interference
- Graded-density depth “d” determines the AR range
  - AR needs $d>\lambda/2$

Background: Confirmed 16.8% Black Si Solar Cell

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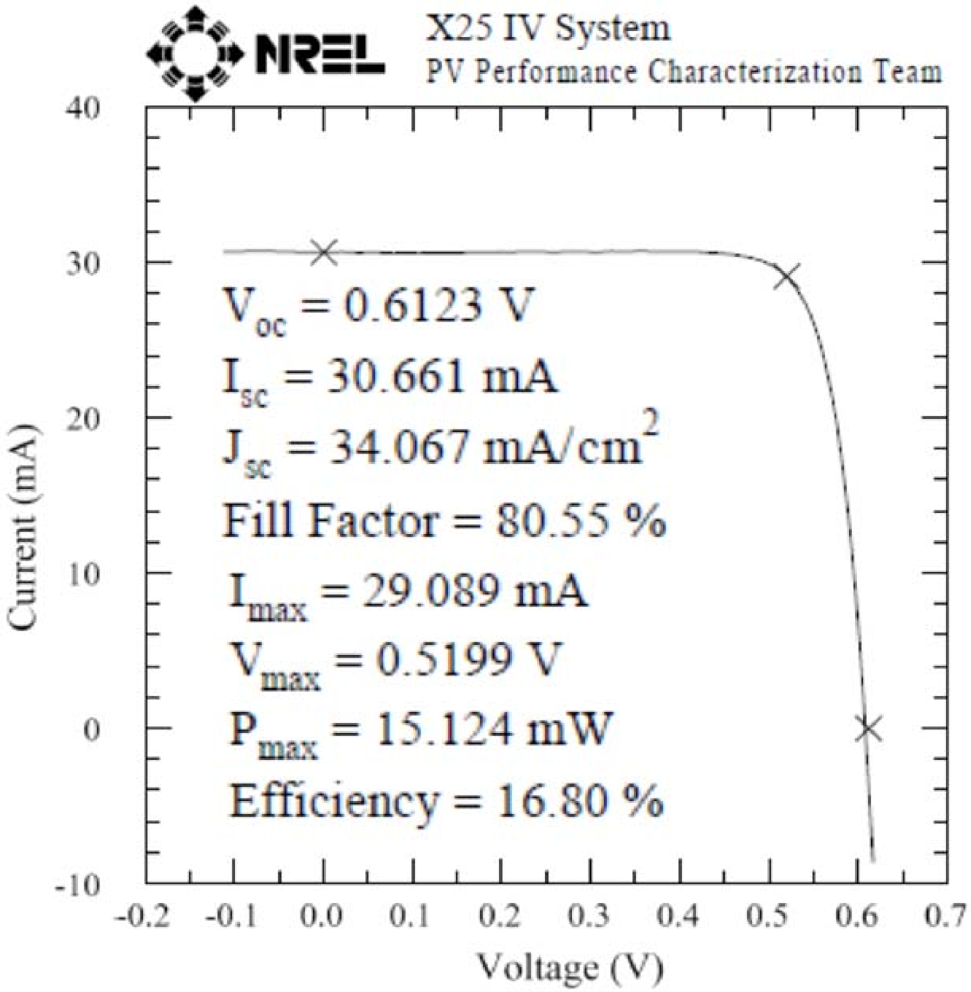
Yuan et al. APL, 2009



- One-step, 3-min, all liquid black Si etch
- No vacuum-based AR coating deposition
- Highest solar energy conversion efficiency reported with black Si AR
- Preliminary 14.9% on multi-crystalline Si

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Key ARRA Objectives

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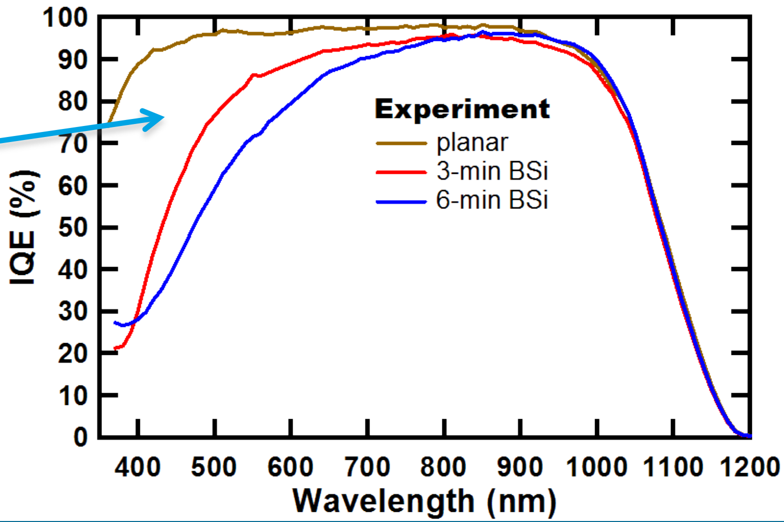
1. Improve black Si solar energy conversion efficiency to 17.8% and 15.8% on mono- and multi-crystalline Si, respectively
2. Apply one-step, all liquid black Si etch to at least four commercial multi-crystalline Si substrates
3. Evaluate angular performance and energy production of black Si solar cells
4. Demonstrate Au recycling method and develop industry-ready black Si etch processes

Approaches for Objective 1: Realize Full Efficiency Potential

- Reduce near-surface doping level to reduce Auger recombination within nano-porous region
- Improve surface passivation on the nano-porous surface
- Modify pore dimension to reduce surface area while keeping the excellent anti-reflection
- Improve backside scattering to increase light path length inside Si

Must improve blue response



Approaches for Objective 2: Apply Black Si on Multi-Crystalline Si

- Acquire industrial multi-crystalline Si substrates from at least four crystalline Si PV companies
- Perform and improve black Si etch process on multi-crystalline Si substrates
- Evaluate solar cells

Approaches for Objective 3: Evaluate Angular Performance

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- Design rotatable stage for angular conversion efficiency measurement
- Measure angular dependent conversion efficiency on black Si solar cell and mini-module
- Estimate annual energy production improvement by use of annual diffuse and specular insolation data

Approaches for Objective 4: Industry-Ready Processes

- Design and demonstrate Au recycling process
- Develop guidelines for design and operation of factory-scale black Si etch equipment

Collaborations / licensing

- Company A has provided both mono- and multi-crystalline Si substrates
- Company B and C have provided mono-crystalline Si substrates
- Company D and E have provided multi-crystalline Si substrates
- Company F has provided multi-crystalline Si ribbons
- Several companies are negotiating for licenses to the patents for the black Si technology

Accomplishments: New Hires

We have assembled an excellent project staff

- Dr. Howard Branz (Ph.D., MIT Physics) Principal Investigator
- Dr. Hao-Chih Yuan (Ph.D., University of Wisconsin Electrical Engineering), designed and fabricated first efficient black Si PV cells, Research Scientist
- Dr. Jihun Oh (Ph.D., MIT Materials Science) Post-doctoral Fellow
- Dr. Fatima Toor (Ph.D., Princeton University Electrical Engineering) Post-doctoral Fellow
- Vern Yost (M.S., Univ. Colorado Denver Chemisty);
- Matt Page (M.E. Colorado School of Mines Materials Engineering)

Accomplishments: Black Si Cost Analysis

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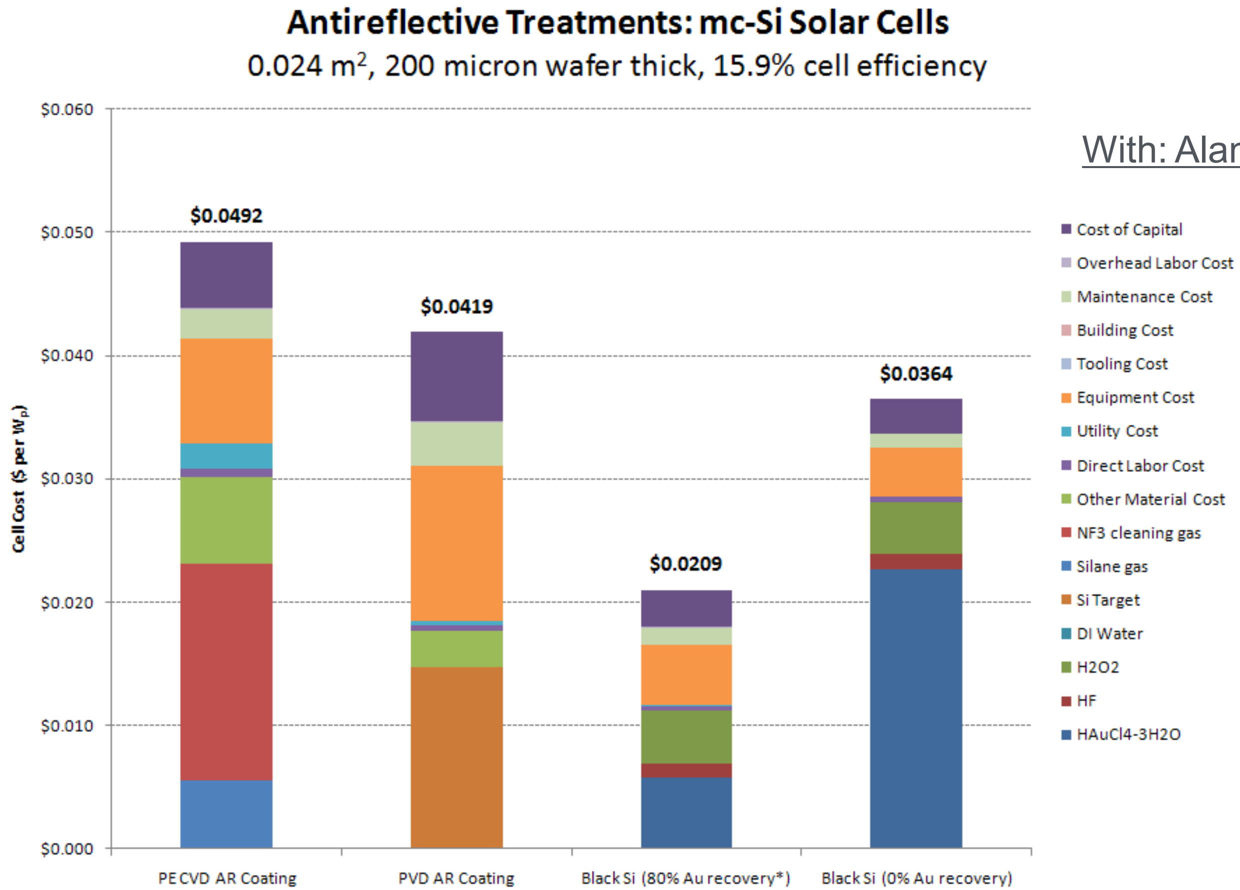

With: Alan Goodrich, NREL

- Assuming same conversion efficiency, black Si saves 2-3 cents/W compared to conventional AR
- 80% Au recycling is required for large cost advantage

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Accomplishments: Black Si Cost & Environmental Impact Analysis In Progress

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	Capex for 200-MW line	Power requirement (kWh/kW)	Equivalent CO_2 (kg CO_2/kW)	GHG emission	Safety
Black Si AR	$67.5M (no Au recovery) $69.1M (80% Au recovery)	110	85	None	None
PECVD AR coating	$75.5M	170	131	NF_3: 17,200x CO_2 SF_6: 22,000x CO_2	SiH_4: toxic, spontaneous flammable
PVD AR coating	$81.2M	120	93		

With : Alan Goodrich, NREL

Black Si AR:

- cost effective
- requires less electricity
- emits no greenhouse gas
- safe

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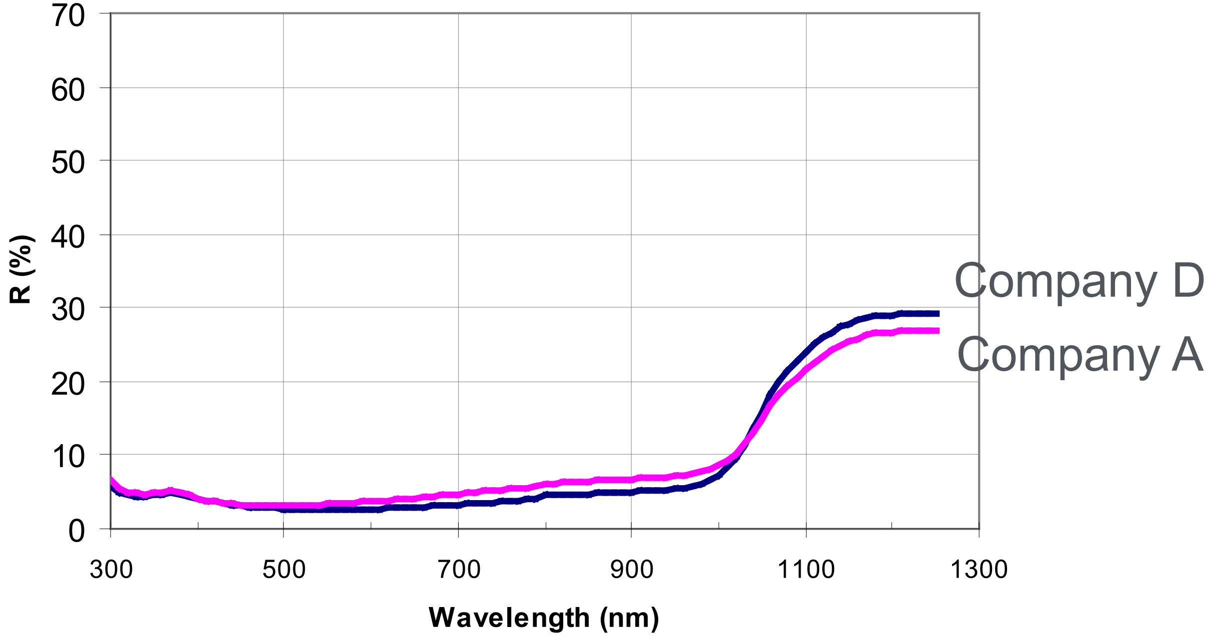
Credit: Alan Goodrich, NREL

Accomplishments: Test Black Si on Industrial Multi-Crystalline Si

- We have acquired industrial multi-crystalline Si substrates from four crystalline Si PV companies
- We have achieved solar-spectrum-weighted (350-1000 nm) average reflectance of 4~6% on multi-crystalline black Si solar cells with 3-min black Si etch from two PV companies. Typical reflectance using conventional AR is > 7%.



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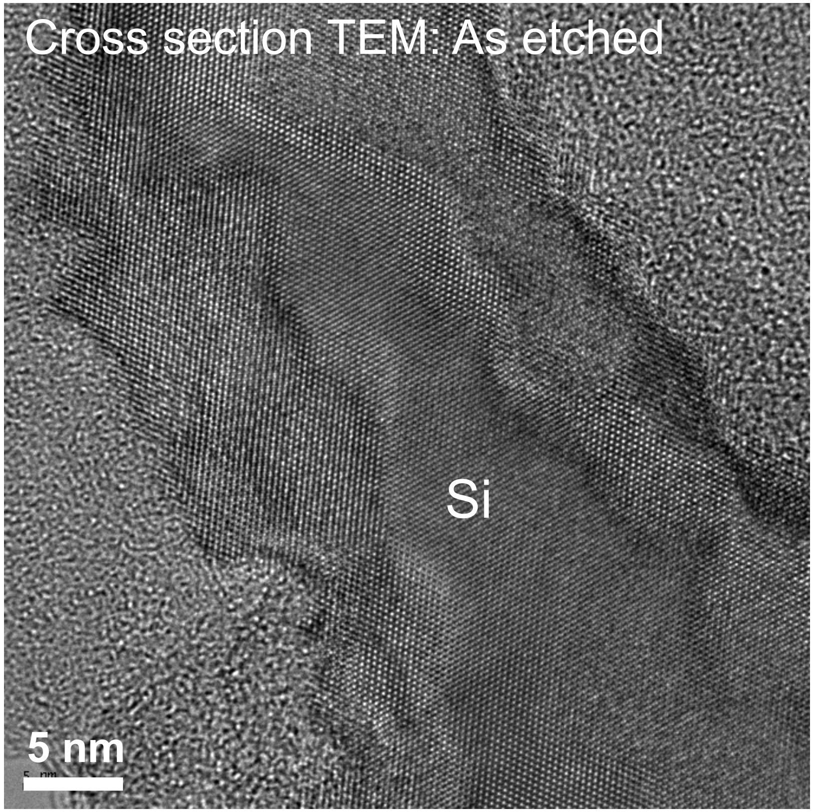
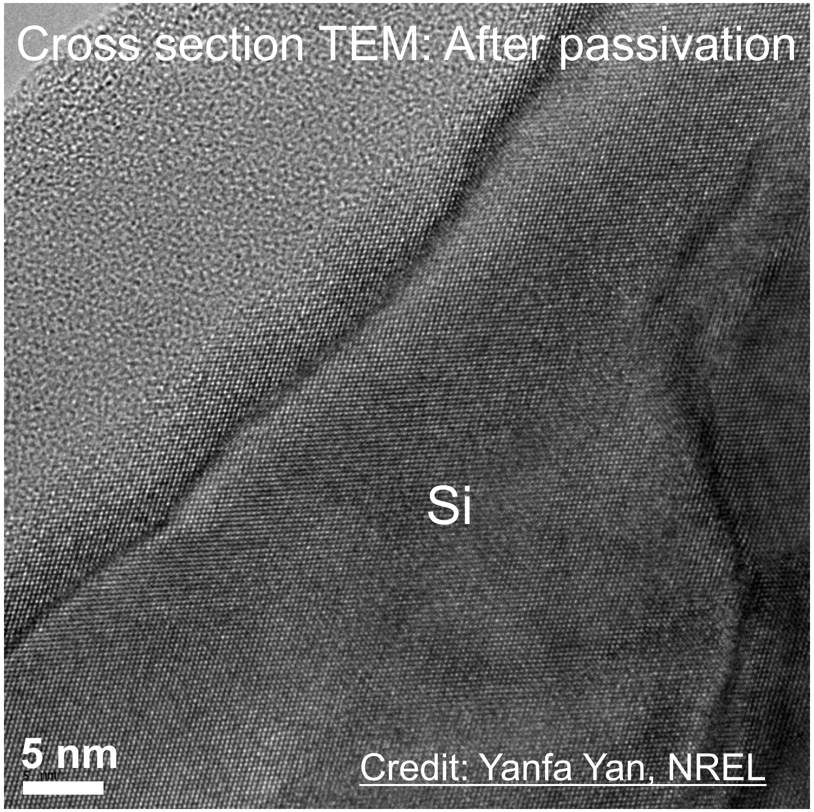
Accomplishments: TEM of Black Si Surface Passivation





- Rough Si and Si-oxide interface resulted from black Si etch makes surface passivation challenging
- Our proprietary manufacturing-compatible passivation process smoothes the interface and improves passivation quality

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Future Plans

- Experiments to determine which is dominant blue loss mechanism
  - Modify doping profile to reduce Auger recombination at near surface region
- Improve black Si etch throughput
- Optimize black Si etch on multi-crystalline Si substrates
- Modify pore dimension to reduce surface area

Upcoming key milestones

• Reduce near surface doping level to ~10^{19} cm^{-3}	Aug. 2010
• Reduce black Si etch time to < 30 sec	Aug. 2010
• Optimize black Si etch on multi-crystalline Si substrates	Oct. 2010
• Increase pore feature size to ~ 40 nm	Dec. 2010

Summary

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- NREL's one-step, all liquid black Si etch creates nanoporous graded-density surface that suppresses reflection over broad spectrum at normal and off-normal angles
- NREL's black Si AR is cheaper, more environmental friendly, and has potential for higher solar energy conversion efficiency than conventional AR techniques
- New surface passivation technique creates smooth interface and improves the passivation quality without increasing manufacturing cost
- Excellent team assembled to address key technical barriers to commercial adoption of black Si technology